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LABORATORY AND FIELD USE OF SOIL TENSIOMETERS ABOVE AND BELOW 0°C

Jonathan E. Ingersoll

UNITED STATES ARMY CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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Methods for using tensiometers in conjunction with moisture retention characteristic curves for non-destructive soil water measurements are presented for above- and below-freezing situations of engineering interest. Four methods for determining moisture retention characteristics, three tensiometer types, and several methods of recording soil suction are discussed. Procedures for preparing, modifying and installing tensiometers for field use in cold climates are explained. Several examples of moisture retention characteristics are

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shown, including the effect of soil density on water retention. Examples of soil tension ahead of and behind a frozen soil zone are also presented.

PREFACE

This report was prepared by Jonathan Ingersoll, Civil Engineering Technician, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was funded under In-House Laboratory Independent Research Project 4A161101A91D, Work Unit 273, Developmental Evaluation of a Tensiometer for Use Under Freezing Conditions.

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ILLUSTRATIONS

LABORATORY AND FIELD USE OF SOIL TENSIOMETERS ABOVE AND BELOW 0°C

by

Jonathan E. Ingersoll

INTRODUCTION

Developing a non-destructive method for determining soil-water volume and moisture flux through soil in the laboratory and in the field has long been a problem. A knowledge of water migration is important in understanding frost heave potential, estimating the degree of strength loss upon thawing, and predicting soil behavior at wastewater land-treatment sites.

One method for non-destructively measuring moisture change is by using tensiometers, which directly measure soil tension (also called matric potential or suction). As tensions measured by the tensiometers increase, the water content of the soil decreases and vice versa. Tensiometers have been used in agriculture for years to guide farmers in crop irrigation. When tensions reach a certain magnitude, the field is irrigated.

Soil-moisture tension values can be converted to water content values using moisture characteristic curves, which can be determined by several laboratory methods (Tanner and Elrick 1958, Reginato and Van Bavel 1962, American Society for Testing and Materials 1970). Each soil has a family of moisture characteristic curves because the size and distribution of voids change as the dry density changes (Fig. 1).

Figure 2 shows typical desorption moisture characteristic curves for sand, silt and clay soils. Coarse-grained soils retain considerably less moisture than silts or clays as soil tension increases.

Unfortunately, moisture characteristic curves are not single-valued. That is, the relationship between moisture content and tension when the soil is being wetted is different from the relationship when the same soil is being dried. This hysteresis effect for a silt is shown in Figure 3.

The equipment I have adapted for my laboratory investigations was, for the most part, developed for agricultural and soil science applications.

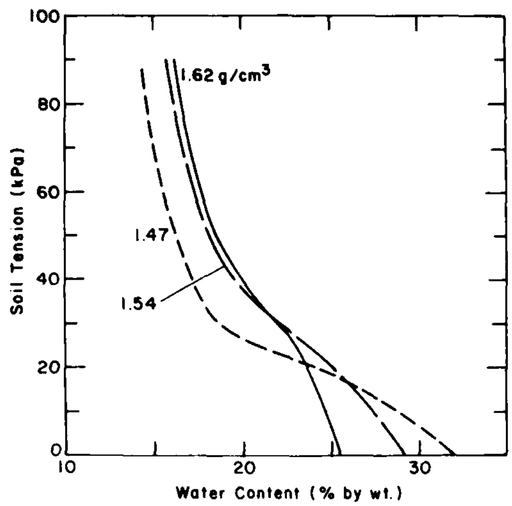


Figure 1. Effect of density on the moisture characteristics of a silt.

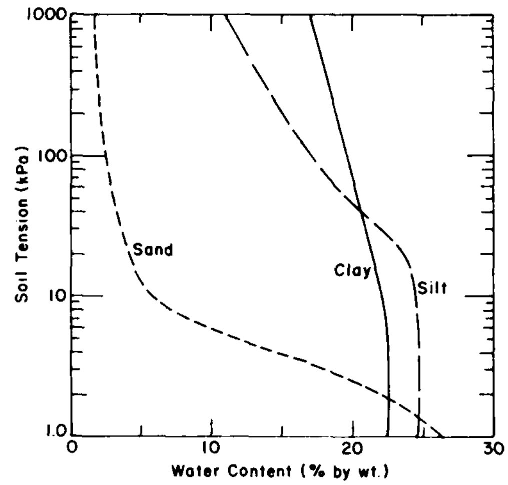


Figure 2. Typical moisture characteristic curves for a sand, a silt, and a clay.

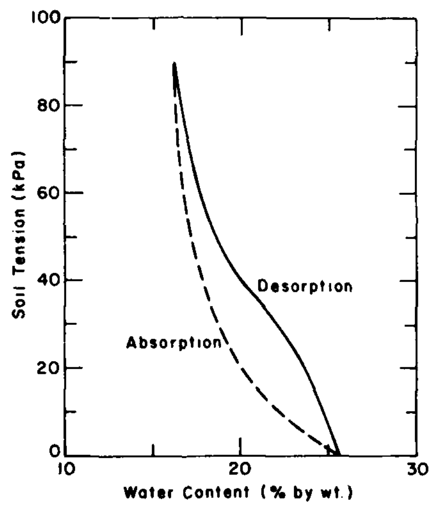


Figure 3. Hysteresis between absorption and desorption phases of the soil tension curve of a silt

Civil engineers will probably use these devices much more in the near future. The primary purpose of this report is to bring these tools to the attention of civil engineers and technicians.

MOISTURE CHARACTERISTIC CURVES

I have used four devices to determine moisture characteristic curves: a Tempe cell, a volumetric pressure plate extractor, a high-pressure plate extractor and a pressure cell permeameter.

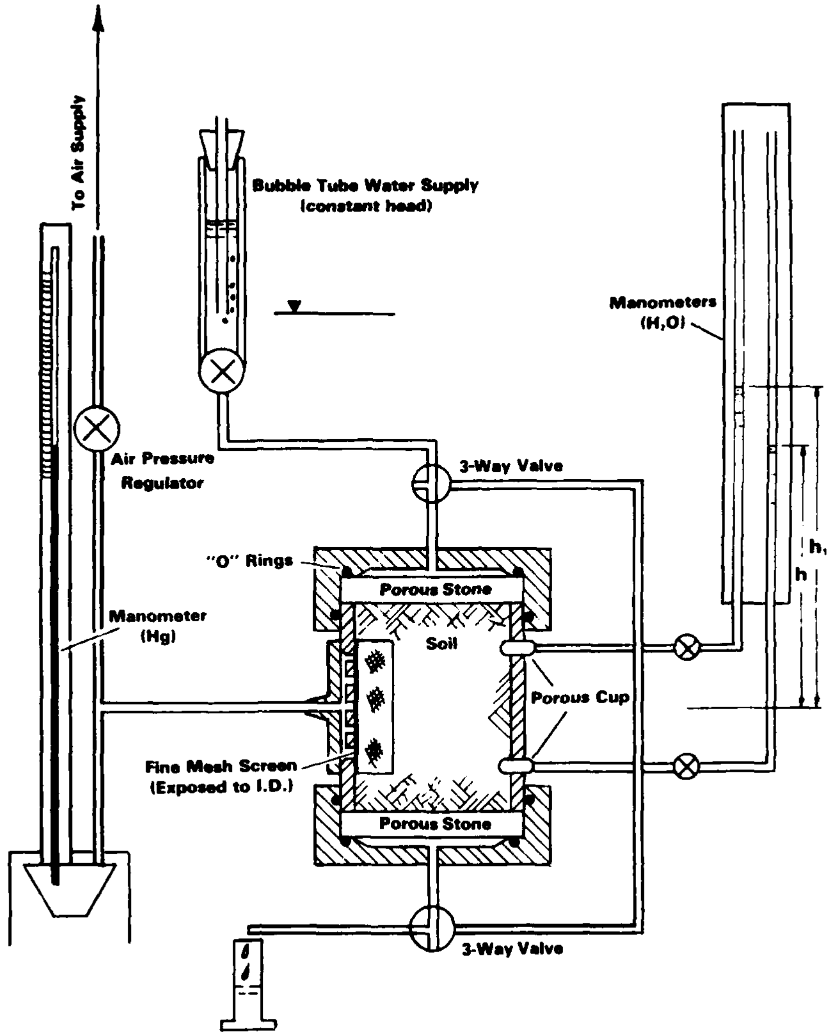


Figure 4. Pressure cell permeameter for measuring saturated and unsaturated hydraulic conductivity and moisture retention characteristics.

The first three are commercial products manufactured by Soilmoisture Equipment Corporation, Santa Barbara, California. The pressure cell permeameter (Fig. 4), developed at CRREL, is similar to devices described by Klute (1965) and Fukuda and Luthin (1980). They apparently used the device to determine only the hydraulic conductivity of unsaturated soils. However, by modifying the cell (Ingersoll 1981), I also use the device for determining saturated hydraulic conductivity and moisture characteristic curves. While the other methods are satisfactory when used within their limitations, I use the pressure cell permeameter almost exclusively because it

1. Allows me to determine both the absorption and desorption portions of the moisture characteristic curves.
2. Restricts any volume change of the soil during absorption.
3. Allows me to determine both the saturated and the unsaturated hydraulic conductivity on the same soil sample during both absorption and desorption.

Tempe cells can determine only the desorption (drying) portions of the characteristic curve, while volumetric pressure plates can provide data for both the absorption and desorption portions of the curve. Both cells can test to only 100 or 200 kPa (1 or 2 bars). The high pressure extractor is used to extend the desorption curves to 1500 kPa and above if desired. (A table showing conversion factors for the many units used for soil tension is included as the Appendix.) To date I have used the pressure cell permeameter to test soils at tensions less than 100 kPa; however, I now have porous stones which have air entry values of about 300 kPa and I will soon begin testing over this range.

All of the above methods use the same principle for determining the moisture characteristic curve: air pressure is applied to the soil, forcing free water from the soil pores. It is generally accepted that pressure applied to the surface produces the same effect as suction applied to the cell outlet, i.e. it is the pressure gradient that causes free water to flow from the pores.

As the total pressure increases, water moves from increasingly smaller pores. The extracted water is measured following each pressure increase. At the conclusion of a test, the volume of water for each increment of pressure is added to the final water content determined gravimetrically to develop the desorption portion of the moisture characteristic curve.

The amount of soil moisture retained when the pressure is increased from 0 to 100 kPa varies widely among different soil types (Fig. 2). At a tension of 100 kPa, sands are only about 10% saturated, silts only about 50%, and clays 90-95%. Because of this, tensiometers function well in sands and silts; however, in soils with high clay content, tensions can only be measured within a narrow range of moisture content. If a clay dries below this range, the suction will exceed 100 kPa and water inside the tensiometers will cavitate and drain from the system.

Two devices are available for indirectly measuring the water content of clay soils: a soil psychrometer, which is a device for measuring the

relative humidity within the soil pores, and an electronic soil-water matric-potential measurement system, which measures the heat dissipation within a calibrated porous stone. The psychrometer system is available from Wescor, Inc., Logan, Utah. The electronic soil-water potential system is distributed by Moisture Control Systems, Findlay, Ohio. I have had no experience with either of these systems, however.

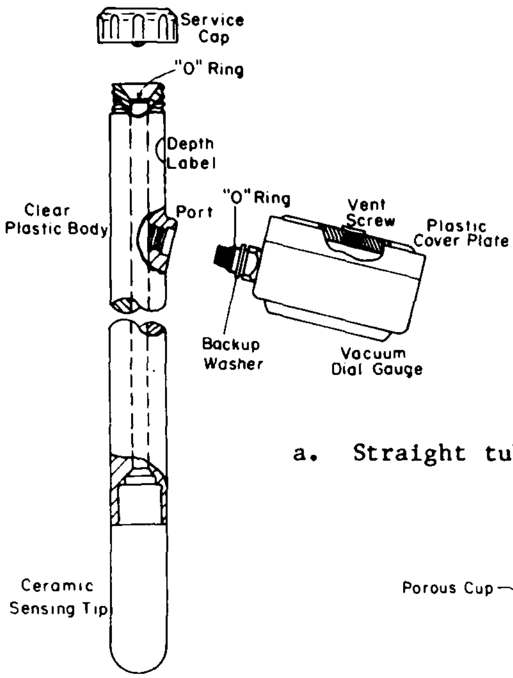
TENSIOMETERS

The primary components of a tensiometer (Fig. 5) are the porous ceramic tip, the reservoir, the connecting tube, the fluid, and the pressure measuring device, which can be a dial gauge, a manometer or an electric pressure transducer. The general principle of the instrument is that the saturated porous ceramic tip becomes an integral part of the soil it is placed in; the soil water and the water in the ceramic tip become a continuous medium. Any stress in the pore water of the soil is felt throughout the column of fluid in the tensiometer, thereby registering on the pressure measuring device attached to the tensiometer reservoir. As the soil loses water, stresses increase through capillary forces. The instrument can measure these stresses until the tension approaches 85 kPa. At this tension, air dissolved in the fluid expands dramatically, causing a loss of fluid through the tip.

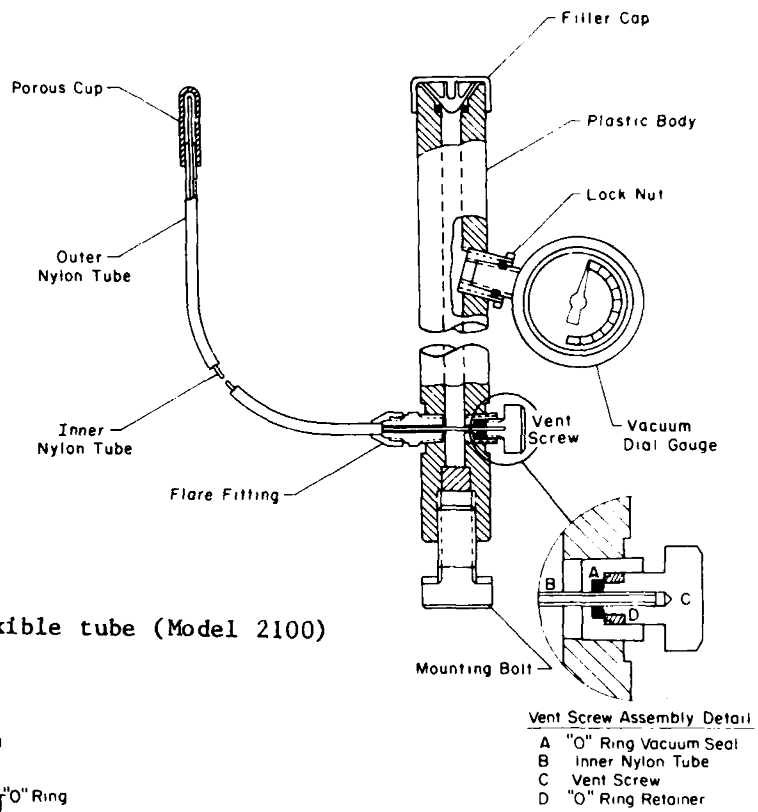
Three tensiometer types are currently in use at CRREL (Fig. 5): straight tube, flexible plastic tube, and dual copper tube.

The straight tube tensiometer (Fig. 5a) is composed of a clear plastic tube 15 to 150 cm long, with an outside diameter of 2.2 cm and an inside diameter of 0.6 cm. A 7.5-cm-long porous ceramic cup is attached to the bottom end. The top of the cylinder is sealed by a cap and an "O" ring. A dial gauge or an electric pressure transducer is attached about 7.5 cm from the top.

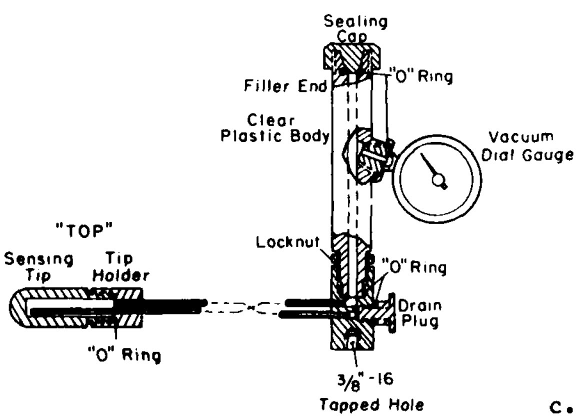
The upper part of the flexible plastic tube tensiometer (Fig. 5b) is similar to that of the straight tube type but is only about 15 cm long. This 15-cm segment serves as a reservoir. Attached to the base of the reservoir is a 1-m-long flexible tube with an outside diameter of 3 mm. (I have successfully used flexible tubes up to 7 m long.) The porous tip, attached to the end of the tube, is usually 2.5 cm long and 0.6 cm in diameter. However, I have successfully attached tips as small as 3 mm by 3 mm for laboratory testing. The flexible tube is actually a tube within a



a. Straight tube (Model 2710)



b. Flexible tube (Model 2100)



c. Dual copper tube (Model 2270).

Figure 5. Three tensiometer models in use at CRREL. (Manufactured by Soilmoisture Equipment Corporation, Santa Barbara, California.)

tube (Fig. 5b). This construction is necessary for purging air from the system. The inner tube extends from the tip, through the outer tube and reservoir to a vent at the base of the reservoir. If a syringe is inserted into this tube, fresh de-aired fluid can be forced through the tip and back to the reservoir, where old fluid and air can escape.

Dual copper tube tensiometers (Fig. 5c) are similar to the flexible plastic tube type. They are much more rugged, however, and have been used in embankments under roadway test sections and airfields. The porous tips are 2.2 cm in diameter and 7.6 cm long. The dual copper tubes are used for purging air from the system. With this type, I have found it more convenient to force new fluid into the top of the reservoir, through the system, and out the vent.

The air entry value (AEV) of a porous ceramic tip or plate is equal to the air pressure necessary to displace any water from its pores. When the tip or plate is saturated, water will flow through it (but air will not) unless the air pressure exceeds the AEV. Therefore, all tips used with tensiometers and all plates used in extraction cells must have AEV's greater than the pressures or suctions expected during testing. Normally the ceramics I have used have AEV's of 100 kPa. However, when moisture retention tests are performed, 200- to 1500-kPa ceramic plates are used, depending on the maximum pressure applied. As the AEV of a porous tip or plate increases, the flow rate decreases. It is therefore desirable to keep the AEV at the lowest practical value.

Because of the low flow rates through the porous tips, I have not used manometers to measure pressures or pressure changes. Dial gauges and electric pressure transducers require a minimal transfer of fluid and therefore respond to pressure changes very rapidly.

De-airing the entire tensiometer system prior to installation prolongs the period before fluid loss becomes critical. De-airing the porous ceramic tip is especially important. If tensions remain below 50 kPa, a well de-aired system may remain unattended indefinitely. At higher tensions, the system requires more frequent servicing.

In all tensiometers now used at CRREL, the entire system can be purged of air without removing the ceramic tip from the soil. When purging is complete, the system regains equilibrium, usually within an hour. Very high tensions take longer to equilibrate, however.

The importance of air-tight connections cannot be overemphasized. I have had moderate success using Teflon tape at the connections. However, I am now using an anaerobic pipe-thread sealant called Swak; I have had excellent success with this product. PVC pipe connectors have been successfully used for attachments in the laboratory. When used outside in cold weather, PVC cracked easily during mounting operations. It is usually much easier to make any modification in the laboratory, where the system can be thoroughly tested under a controlled vacuum.

When freezing temperatures are expected, a solution of ethylene glycol and water can be used successfully as the tensiometer fluid. The solution should be kept as weak as possible, as the effect of glycol in the soil is not entirely known. My tests have shown, however, that small quantities of glycol entering the soil-water system do not affect the tension measurements appreciably in unfrozen soils.

The following conditions may cause fluid to flow into the soil from the tensiometer system: 1) changing fluid temperature, 2) air entering the system, or 3) servicing of the tensiometers. Because temperature fluctuations are the greatest cause of fluid flow, it is helpful to insulate the exposed reservoirs in field installations. An insulated box over several reservoirs or individual insulating bags over single units have worked well. A thick snow cover also offers significant insulation.

Fluid contraction during cold periods will cause soil water to enter the system and dilute the solution. This may cause ice crystals to accumulate in the reservoir and may eventually damage the dial or electric pressure transducer. If the fluid freezes in the Bourdon tube in the dial gauge, the U-shaped tube tends to straighten until the needle "pins." If the movement continues, calibration is lost and the dial may eventually be destroyed. Many times, however, the dial can be thawed and recalibrated if freezing was not too severe.

Other factors limiting tensiometer application are the height of the fluid column in the system and the atmospheric pressure. As previously stated, 85 kPa of tension is the practical limit at sea level. The limit decreases at higher elevations. The effective range also decreases as the height of the column of fluid increases. A 150-cm-long tube reduces the operational limit to approximately 70 kPa.

RECORDING SOIL TENSION MEASUREMENTS

Tensiometers are received from the manufacturer equipped with Bourdon-type dial gauges graduated from 0 to 100 centibars (1 cbar = 1 kPa). The dial gauges work well in laboratory and field installations under most normal conditions. They are affected by temperature changes because air trapped in the hermetically sealed rubber case expands and contracts. These volume changes cause pressure changes within the gauge, affecting the Bourdon tube. The pressure must be relieved by loosening the screw in the center of the face plate before making an observation. The screw should be retightened after the reading (especially in the field) to keep condensation and rainwater from accumulating within the dial and rusting the components.

The dial can be "zeroed" before the gauge is installed to account for the column of water between the gauge and the tip. It may be preferred, however, to deduct this column height from each reading after installation. On straight tube tensiometers, the height is usually printed on the reservoir just above the dial. The difference in elevation must be calculated or measured for flexible tube systems.

Tensiometers can easily be calibrated in the field or laboratory using a small, hand-operated vacuum pump (available from Soilmoisture Equipment Corporation). This pump fits against the "O" ring at the top of the reservoir. Attached at the base is a dial gauge which indicates the tension within the system. A comparison of the dial gauges on the tensiometer and vacuum pump is all that is needed for the calibration. Again, the height of the column of water must be considered. If adjustments are needed, the indicator needle on the dial on the tensiometer can be moved using a small screwdriver. This can all be done without removing the tensiometer from the soil. If positive pressures are expected, the indicator needle on the dial can be offset, allowing it to move in a positive direction without touching the pin. This offset will change the actual zero position and must be considered in subsequent observations.

If automatic data acquisition is desired, electric pressure transducers can easily be used with or in place of the dial. Any pressure transducer that is capable of sensing negative pressures within the 0- to 100-kPa range will do.

Currently I am using a Model PLC transducer manufactured by Celesco Transducer Products, Inc., Canoga Park, California. It is small and

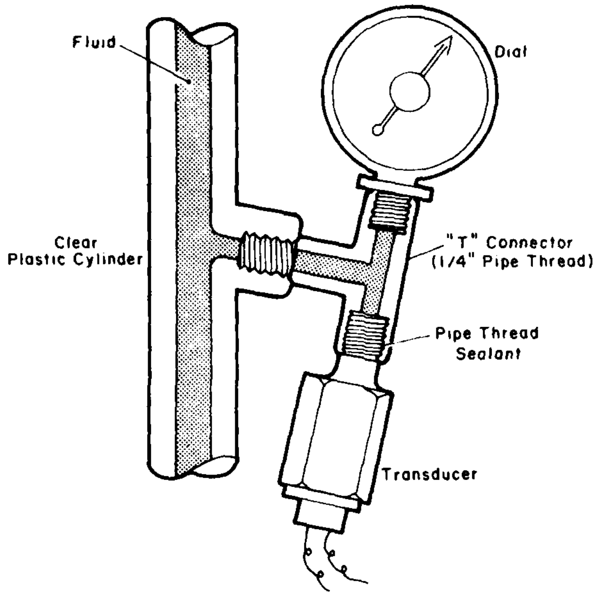


Figure 6. Modification of a tensiometer by attaching a pressure transducer for automatic data collection.

durable and has a pressure port connector threaded with 1/4-in. (6-mm) NPT (National Pipe Thread), which is the same thread size as the dial gauge ports on the tensiometers. It is powered by a 10-V DC power source. In many cases I attached both a transducer and a dial gauge to the tensiometer using a brass, 1/4-in. (6-mm) pipe "T" connector (Fig. 6). This offers a good check for each.

A device called the Scanivalve can record tensions from up to 12 tensiometers electronically using one pressure transducer (Williams 1978). This device is manufactured by Scanivalve, Inc., San Diego, California. I have had no experience with it.

In several instances I needed a method of automatic data acquisition from installations at distant or remote sites. For these locations, tensiometers were modified by adding a pressure transducer. The transducer was connected to a relay transmitter within a data collection platform, which periodically transmitted data to an orbiting satellite. This system is described by McKim et al. (1976).

DE-AIRING THE SYSTEM

A thorough de-airing of the entire system is most important, especially if tensions above 50 kPa are expected. If the tensiometers are

observed each day, it may not be necessary to follow the full de-airing procedure, as air can be eliminated daily. The manufacturer supplies a procedure for de-airing that is adequate for those conditions. For long-term unattended installations, I have found it beneficial to follow the full de-airing procedures. The same basic procedure is followed for the three types of tensiometer.

To de-air the system, the porous ceramic cup is inserted in a filtering side-arm flask and made airtight. For the straight tube tensiometer, an "O" ring slipped over the porous cup will make a good seal with the neck of the flask. For the flexible tube model, a one-hole stopper with a slit down one side can be used. A plastic moldable material can be used to seal the openings. For the dual copper tube model, a two-hole stopper with a slit on both sides and with sealed openings works well.

A "T" connector is then attached to the flask's arm port with plastic tubing. A tube from one arm of the "T" goes to a de-aired fluid source and the other to an aspirator or vacuum pump. With the entire system sealed, the vacuum system is activated, de-airing the entire tensiometer.

After 30 minutes or so, the de-aired fluid is allowed to flow into the flask while the system is still under a vacuum. When the porous ceramic cup is fully submerged in the fluid, the vacuum line is detached from the "T" connector, exposing the fluid to atmospheric pressure. The fluid will then immediately enter the porous ceramic cup and fill the tensiometer. To speed the entry of fluid, a 1/4-in. OD plastic tube is inserted through the "O" ring in the top of the reservoir. This is then connected to a vacuum source. If the fluid is clear as it fills the reservoir, the tip is well de-aired. If the water appears frothy, air is still coming from the ceramic. If a series of large bubbles appears from the base of the reservoir, there may be a leak in the system that requires attention. If bubbles come from the dial connection, air may still be locked in the Bourdon tube within the gauge. This can be removed by releasing and reconnecting the vacuum line several times. The vacuum should be released gradually, as sudden releases can damage the dial gauge needle.

This de-airing procedure does not work well if the porous tip is wet or saturated before the initial de-airing. Because of the high AEV, air from within the tensiometer will not pass through the wet stone. If this happens, place the tip in de-aired fluid and insert the 1/4-in. OD tube in the top of the reservoir. Draw the fluid through the entire system until

all the air has disappeared. This may take some time, but eventually the air will be forced out.

If a leak has developed in the flexible tube connection to the reservoir on the tensiometer, repairs can be made by disconnecting the tube at the reservoir. The smaller inner tube extends through the reservoir to the vent. The larger tube is flared at the end and presses against a brass fitting. Cut the outer tube back 3 cm or so but do not puncture the inner tube. Push the inner tube back as far as possible toward the tip. It will wrinkle in the tube and stay out of reach. Reflare the outer tube using a regular pipe flaring tool. Pull the inner tube out 4 cm or until it will extend through the reservoir. Pass a needle through the vent hole and reservoir and into the inner tube to use as a guide. The inner tube is then threaded through the base and should extend by 1 cm. Reconnect the outer tube and replace the vent cap. Refill the system and check it for leaks.

Air entering the system of an installed tensiometer usually accumulates in the reservoir, causing the fluid level to drop. The tension values are not seriously affected unless the fluid drops below the level of the port. This is always true with the straight tube tensiometers, but in flexible tensiometers, air may stay lodged in the tip or in the tube, especially if the tubes are horizontal. Flexible tube tensiometers should therefore be purged of air more frequently. It is best to use de-aired fluid for purging; however, when sites are visited frequently and tensions are low, any water will do.

Water can be de-aired in several ways. Agitation while under a vacuum for several hours is a good method. Boiling usually de-airs the water sufficiently. When de-airing solutions of ethylene glycol and water, I have found it more efficient to de-air the glycol and water separately before combining them.

INSTALLATION

I normally fill the tensiometers in the laboratory, where I have much better control of the de-airing and filling processes. Laboratory-filled tensiometers have performed more successfully than field-filled ones.

When a filled tensiometer is being transported to the installation site, the porous tips must be kept moist. This can be done by wrapping the tips in wet tissue or inserting them in water.

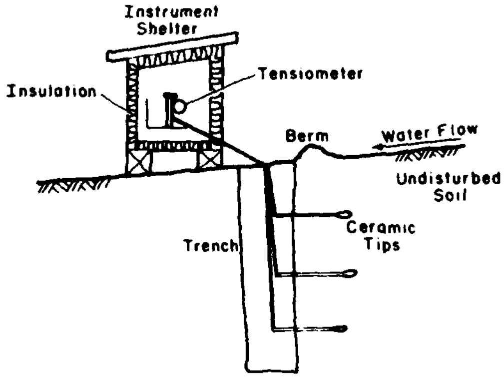


Figure 7. Field installation using flexible tube tensiometers.

To install a straight tube tensiometer, a 2.5-cm diameter hole is first augered to the depth desired. If an "insertion tool" is available from the manufacturer, the final 7 1/2 cm can be made exactly the same diameter as the tip, assuring good soil contact. (In shallow sand or silt, the insertion tool may be all that is necessary to make the hole.) If soil contact is good, tension readings should appear immediately unless the soil is saturated.

If an insertion tool is not available, the tensiometer can be set in the augered hole and the entire hole can be backfilled. Tests have shown that it is desirable but not necessary to backfill with soil from the augered hole. A soil of similar texture or one with a finer grain size distribution can be used. Both a slurry and a dry soil have been used as backfill with good results. When a slurry is used, I agitate the tube when pouring in the backfill. I then compact the surface adjacent to the tube into a conical shape to reduce the possibility of water piping down the side.

When flexible tube tensiometers are being installed, it is usually necessary to dig a trench to the depth of the deepest tensiometer. When the soil is undisturbed, consideration should be given to the slope of the land and the direction of surface drainage. In most cases I have inserted the tensiometers horizontally into holes that penetrate several inches into the wall of the trench (Fig. 7). The tube runs vertically to the instrument shelter. The trench is then backfilled and compacted as close to the original density as possible. It may be desirable to construct a slight berm to deflect surface water away from the disturbed soil in the trench.

It is necessary to determine the difference in elevation between the reservoir and the tensiometer tip for later corrections.

When dual copper tube tensiometers are being installed, a similar procedure is followed. I have used this type under pavements on airfields and roadways. A trench is dug from the test site in the road bed to the instrument shelter at the edge of the pavement. The ceramic sensors lie on their sides with the copper tubing running horizontally to the shelter. There is a top and bottom marked on the ceramic sensor. This is necessary, as the shortest tube within the cup must be at the top to allow air to escape during purging.

Good soil contact is a prime concern during installation. In silt and sand, there is little difficulty. When placing a tensiometer in gravelly material, I assure good soil contact by placing sand around the ceramic cup. This also cushions the cup somewhat when replacing the gravel.

LABORATORY APPLICATIONS

Tensiometers can give important data in most any laboratory testing where soil moisture flux is a factor. One such application is in frost heave studies. Not only do tensiometers register the high suction created in and near the freezing zone, but they detect the change in tension as water flows through the soil toward the freezing zone (Fig. 8). Figure 9 shows a comparison of tension profiles as rapid frost penetration occurs in a silt and in a gravel.

A study is underway to determine the relatively high tension gradient created within a freezing zone. Special tensiometer tips were roughly cut from large ceramic tips and sanded to a teardrop shape (3 mm by 3 mm). The pointed end was epoxied to the end of a flexible plastic tube tensiometer.

Tensiometers are valuable tools for studying not only freezing soils but also thawing soils. They have been used in studying the recovery of strength of soils during and after thaw.

A method for rapidly determining the moisture retention characteristics of undisturbed soil has been attempted. A tensiometer was placed in the center of each of eight cylinders of soil. The soil was saturated and then allowed to dry to varying degrees. The tensions were recorded, the soil was oven-dried, and a curve for tension vs water content was produced.

Other applications include hydraulic conductivity, slope stability, soil stress and infiltration studies.

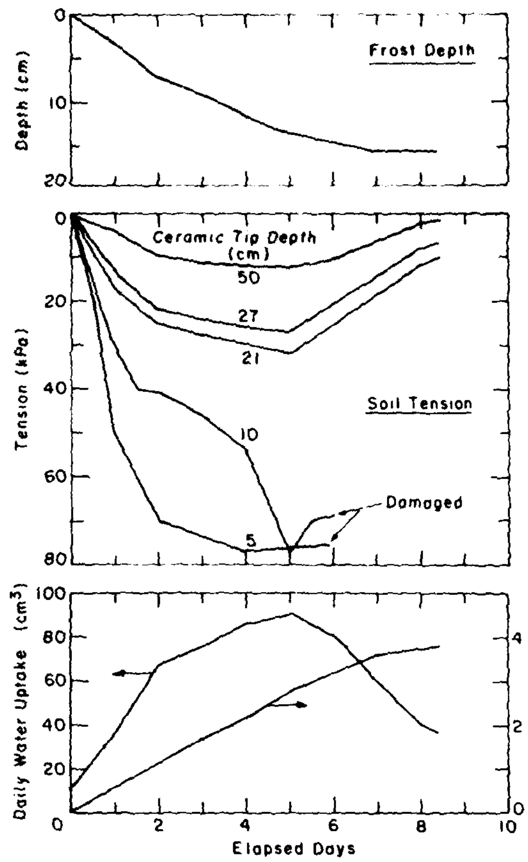


Figure 8. Frost depth, soil tension, water uptake and heave measured with an instrumented soil column.

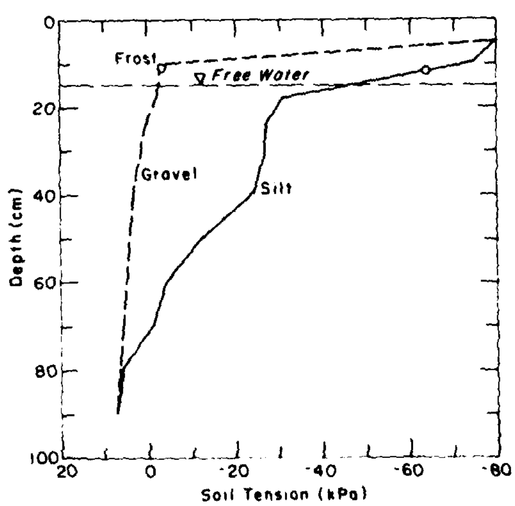


Figure 9. Tension profiles during rapid frost penetration of a 1-m-long soil column.

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APPENDIX: CONVERSION TABLE FOR SOIL TENSION UNITS

To convert soil tension values from one set of units (shown on left) to another (shown across the top), multiply by the appropriate conversion factor. For example, multiply inch Hg by 2.54 to get cm Hg.

Unit	cm H_2O	cm Hg	in. Hg	dynes/cm^2	bar	atm	psi	kPa	in. H_2O	ft H_2O
cm H_2O	1	.0737	0.0290	981	9.81×10^{-4}	9.68×10^{-4}	0.0142	0.0981	0.394	0.0328
cm Hg	13.57	1	0.394	1.33×10^{4}	0.0133	0.0131	0.193	1.331	5.35	0.445
in. Hg	34.47	2.54	1	3.38×10^{4}	0.0338	0.0334	0.489	3.38	13.58	1.13
dynes/cm^2	10.2×10^{-4}	0.751×10^{-4}	0.296×10^{-4}	1	1×10^{-6}	93.6×10^{-6}	0.145×10^{-4}	1×10^{-4}	4.01×10^{-4}	0.334×10^{-4}
bar	1019	75.1	29.55	1×10^{6}	1	0.986	14.47	100	401	33.4
atm	1033	76.1	29.96	1.01×10^{6}	1.013	1	14.67	101.3	407	33.9
psi	70.23	5.18	2.04	6.89×10^{4}	0.0689	0.068	1	6.89	27.7	2.30
kPa	10.19	0.751	0.296	1×10^{4}	0.0100	98.5×10^{-4}	0.145	1	4.01	0.334
in. H_2O	2.54	0.187	0.0737	2492	24.9×10^{-4}	24.6×10^{-4}	0.0361	0.249	1	0.0833
ft H_2O	30.48	2.25	0.884	2.99×10^{4}	0.0299	0.0295	0.433	2.99	12.0	1
pF*										

*pF units are the log of the matric suction when expressed as cm H_2O.

1 dyne/cm^2 = 1 erg/g
1 kPa = 1 joule/kg

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